AD-A069 497 INDIANA UNIV AT BLOOMINGTON DEPT OF CHEMISTRY F/G 20/5
WIDE-BANDWIDTH ANALOG CORRELATOR AND ITS APPLICATION TO MODE-LO--ETC(U)
MAY 79 J M RAMSEY, G M HIEFTJE, G R HAUGEN N00014-76-C-0838
UNCLASSIFIED TR-19 NL

| OF |
AD
A069497

END
DATE
FILMED
7--79
DDC

BS 12

LEVEL II

AD A069497

OFFICE OF NAVAL RESEARCH

N00014-76-C-0838

Task No. NR 051-622

TECHNICAL REPORT NO. 19

WIDE-BANDWIDTH ANALOG CORRELATOR AND ITS APPLICATION TO MODE-LOCKED LASER MEASUREMENTS

by

J. M. Ramsey, G. M. Hieftje and G. R. Haugen

Prepared for Publication

in

REVIEW OF SCIENTIFIC INSTRUMENTS

Indiana University

Department of Chemistry

Bloomington, Indiana 47401

May, 1979

Abstract:

A new instrument for the analog determination of correlation functions of wide-bandwidth signals is described and characterized. The instrument is comprised of microwave electronic components; a double-balanced mixer performs the multiplication operation involved in the correlation process whereas a constant-impedance line stretcher introduces the variable delay. Measurements indicate that the correlator has a bandwidth of approximately 4 GHz. It is shown that this inexpensive and simple device can be used as a diagnostic tool for mode-locked argon-ion lasers when used in conjuction with a fast photodiode detector.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

12

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NINETEEN	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 Wide-Bandwidth Analog Correlator and Its Application to Mode-Locked Laser Measurements		5. TYPE OF REPORT & PERIOD COVERED 9 Interim Technical Report
		6. PERFORMING ORG. REPORT NUMBER 25
7. AUTHOR(s) 10 J. M. Ramsey, G. M. Hieftje ~~and~~ G. R. Haugen		8. CONTRACT OR GRANT NUMBER(s) N000-14-76-C-0838
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Chemistry Indiana University Bloomington, IN 47405 11 10 May 79		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR 051-622
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Washington, D. C.		12. REPORT DATE May 10, 1979
		13. NUMBER OF PAGES 21
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) 15 N00014-76-C-0838		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited 12 23 p.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

14 TR-19

18. SUPPLEMENTARY NOTES

Prepared for publication in Review of Scientific Instruments

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

correlation, high frequency signal analysis, mode-locked laser measurements, time-resolved spectroscopy

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A new instrument for the analog determination of correlation functions of wide-bandwidth signals is described and characterized. The instrument is comprised of microwave electronic components; a double-balanced mixer performs the multiplication operation involved in the correlation process whereas a constant-impedance line stretcher introduces the variable delay. Measurements indicate that the correlator has a bandwidth of approximately 4 GHz. It is shown that this inexpensive and simple device can be used as a disgnostic tool for mode-locked argon-ion lasers when used in conjuction with a fast photodiode detector.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

176 685

79 05 30 214

I. Introduction

Power spectral density and correlation measurements have long been utilized in communications engineering and physics, and are becoming important techniques for the chemist.[1-5] At low frequencies (below 1 MHz) these measurements can be performed quite well with commercially available equipment. However, high frequency (several GHz) signal analysis is far more difficult. At these high frequencies, power spectral density analysis can be performed with existing microwave spectrum analyzers (cross-power spectral density cannot), although such devices are expensive. One scheme for determining correlation functions for wide-bandwidth signals has been reported which involves the utilization of a dual-channel sampling oscilloscope.[6] However, this latter approach is quite expensive to implement.

In the present paper an instrument is introduced which can determine correlation functions for wide-bandwidth signals which are either periodic, or random and stationary. Basically, the instrument evaluates the correlation function through use of a constant impedance line stretcher as a delaying element and a microwave double-balanced mixer as a multiplier. For a given delay, set by the line stretcher, the output of the mixer is low-pass filtered to yield a DC level which corresponds to the magnitude of the correlation function at that delay. This new approach is very inexpensive to implement and easy to use.

In the following sections, the theory of operation of the new instrument will be developed and the device will be demonstrated in the measurement of mode-locked laser pulses.

II. Description of the Instrument

Fig. 1 shows a schematic diagram of the new instrument configured in this case for an autocorrelation determination. The signal to be autocorrelated is applied to the open port of a broadband power splitter. This particular power splitter (Model 874-TPD, GenRad, Concord, MA) is a 6db unit usable over the frequency range 0-8 GHz. The signal from one output port of the splitter traverses a fixed length of transmission line to either of the input ports of a double-balanced mixer (Model MD-525-4, Anzac, Waltham, MA). This transmission line is made up of 4 ns of air-dielectric coaxial line (Model 874-L30L, GenRad, Concord, MA). The signal leaving the other port of the power splitter travels through a variable-length transmission line to the other mixer input port. This variable-length transmission line is constructed of a 1 ns fixed-length air-dielectric line (Model 874-L30L, GenRad, Concord, MA) and a constant-impedence variable-length line (Model 874-LTL, GenRad, Concord, MA). The length of this line can be varied over a range corresponding to a time delay difference of 1.5 ns. In this configuration, the variable line is slightly shorter than the fixed line when the variable delay line is at its minimum delay. Thus a full scan of the attainable relative delay values includes the $\tau = 0$ condition. The mixer is a broadband device which serves as a signal multiplier over the frequency range 5-4000 MHz. With this particular mixer, information in the 0-5 MHz region is lost; clearly, different frequency bands could be covered with alternative mixers. The output at the IF port of the mixer is then processed by a low-pass filter, amplified with a DC amplifier and readout on a digital voltmeter or strip chart recorder. With this arrangement, the autocorrelation function can be obtained over a 1.5 ns delay range.

The autocorrelation instrument shown in Fig. 1 can be readily modified to perform cross-correlation as well. To perform cross-correlation, the respective signals would be sent directly into the mixer via the fixed and variable delay lines. In either of these correlation experiments, the 1.5 ns portion of the correlation function which one wishes to observe can be controlled by adjusting the length of the fixed delay line.

III. Theoretical Description of the Instrument's Output

In this section the output of the correlator will be formulated for the case of an autocorrelation determination. The autocorrelation function, $C_{ii}(\tau)$, for some time-varying signal, $i(t)$, is

$$C_{ii}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} i(t)\, i(t+\tau)dt. \tag{1}$$

Of course, Eq. (1) only applies to a signal which is non-square integrable. Eq. (1) indicates that the time average of the time-dependent product, $i(t)\, i(t+\tau)$, is to be found for each value of τ for which one desires the magnitude of the autocorrelation function. In turn, the time average of this product is just the magnitude of its zero Hz (DC) frequency component, which can be instrumentally obtained with a simple low-pass filter. A requirement for this low-pass filter is that its high-frequency cut-off be well below the lowest significant frequency contained in the product signal. Conveniently, DC electronics can be used beyond the mixer IF port.

To accurately model the instrument shown in Fig. 1, the frequency or impulse response of the various components must be introduced into Eq. (1).

Of course, each component will have its own response and should be rigorously included in the treatment. However, two factors are especially important and will be introduced here: the impulse response of the transmission lines (in this case it will be assumed that they are both equal) and the response of the mixer ports. This latter factor accounts for the filtering characteristics of the mixer ports. These two factors can be combined by utilizing the convolution integral. That is,

$$h_{\ell m}(t) = \int_{-\infty}^{\infty} h_{\ell}(\gamma)\, h_{m}(t-\gamma)\, d\gamma \tag{2}$$

where h_{ℓ} and h_{m} are the impulse response of the transmission lines and the mixer ports respectively, and $h_{\ell m}$ is the combined impulse response of the transmission line and the mixer port. Incorporating Eq. (2) into Eq. (1) and performing the t and y' integrations gives Eq. (3).

$$C'(\tau) = k\int_{-\infty}^{\infty} C_{hh}(\alpha)\, C_{ii}(\tau-\alpha)\, d\alpha \tag{3}$$

Eq. (3) indicates that the output of the new autocorrelation instrument $C'(\tau)$ is the convolution of the true autocorrelation function, C_{ii}, of the signal i(t) and the autocorrelation, C_{hh}, of the instrumental response parameter, $h_{\ell m}$. Clearly, the instrument response function for the correlator, C_{hh}, must be as short in duration as possible to yield an instrument output $C'(\tau)$ that closely approaches the true correlogram. In Eq. (3), k is a scaling factor which accounts for losses in the system.

IV. Demonstration of the Instrument

As a demonstration of the new instrument's utility, the autocorrelation function of mode-locked laser pulses was determined. Correlation techniques have previously been used in laser pulse measurements, but in those cases the correlation process was implemented through optical means[7,8], rather than electronically. In the present experiment, a mode-locked laser was used to irradiate a fast photodiode; in turn, the photodiode signal served as the input to the correlator of Fig. 1.

The detector in these experiments is a specially constructed Schottky photodiode which has an impulse response with a full-duration at half-maximum (FDHM) of less than 50 ps[9]. The radiation from the laser is focused to a diffraction-limited spot by a 3 cm biconvex lens. This focusing is required because the active region of the photodiode is only a small annular region approximately 10 μm wide.

Two different laser sources were utilized in these experiments. Examined first was a synchronously pumped dye-laser system using a mode-locked argon-ion laser (Model 171-09 Ar^+ laser and Model 361 acousto-optic mode locker, Spectra Physics, Mountain View, CA) as the pump. Second, the mode-locked argon-ion laser itself was observed. This mode-locked argon-ion laser was operated at 38 A of plasma current in all experiments to yield 740 mW of average optical power at 5145 Å in the mode-locked condition. In this situation, the laser output consists of a train of optical pulses that are approximately 150 ps in duration and separated by approximately 12 ns. Rhodamine-6G was used in a Spectra Physics Model 375 dye head with an extended front mirror to comprise the synchronously-pumped dye-laser cavity. When the mode-locked argon-ion laser is used to pump this dye laser and the optical cavity spacing of the dye laser matches the cavity spacing of the argon-ion laser, the dye laser becomes mode locked.[10] The output from this dye laser then consists of a pulse train with a period of approximately 12 ns, and with each pulse having a duration of approximately 30 ps as determined through streak camera measurements. The average power from the synchronously pumped dye laser was 40 mW.

The temporal behavior of the output of these lasers can be described by an equation of the following form:

$$\ell_e(t) = \sum_{n=-\infty}^{\infty} \int_{-\infty}^{\infty} \ell(\lambda)\,\delta(t-nT-\lambda)\,d\lambda \tag{4}$$

where ℓ is the function describing the shape of a single pulse, δ is the Dirac delta function and T is the period of the pulse train. The signal from the photodiode, when it observes the time-dependent optical irradiance described by Eq. (4), is then

$$P(t) = \sum_{n=-\infty}^{\infty} \iint_{-\infty}^{\infty} \ell(\lambda)\, h_d(\alpha)\, \delta(t-\alpha-nT-\lambda)\,d\alpha\, d\lambda \tag{5}$$

where h_d is the impulse response of the photodiode. In the present experiment, P(t) is the signal that is processed by the correlator. To derive a relation for the output of the correlator in this experiment, one must first find the correlation function of P, C_{pp}. This correlation function, C_{pp}, is found by substituting P(t) for i (t) in Eq. (1). Making this substitution and performing the appropriate integrations yields

$$C_{pp}(\tau) = \sum_{i=-\infty}^{\infty} \frac{1}{T}\int_{-\infty}^{\infty} C_{\ell\ell}(\tau+iT-r)\, C_{dd}(r)dr \tag{6}$$

where C_{dd} is the autocorrelation of the detector impulse response function and $C_{\ell\ell}$ is the desired information, i.e. the optical irradiance autocorrelation function. Significantly, $C_{\ell\ell}$, the autocorrelation of the periodic function ℓ_c is periodic itself and with the same period T.

To find the output of the correlator for the input signal, P(t), Eq. (6) must be substituted into Eq. (3) [i.e. $C_{pp}(\tau)$ replaces $C_{ii}(\tau)$ in Eq. (3)]. This substitution yields

$$C'(\tau) = \frac{k}{T} \sum_{i=-\infty}^{\infty} \iint_{-\infty}^{\infty} C_{hh}(\alpha)\, C_{dd}(r)\, C_{\ell\ell}(\tau+iT-r-\alpha)drd\alpha. \tag{7}$$

Eq. (7) indicates that the output of the correlator is a smoothed version of the true optical irradiance autocorrelation function. In turn, the smoothing function is the convolution of the autocorrelation of the photodiode impulse response, h_d, and the autocorrelation of the correlator input impulse response, $h_{\ell m}$. Obviously one wants to decrease the duration of both h_d and $h_{\ell m}$.

Fig. 2 reveals the performance of the correlator in the measurement of pulses from the synchronously pumped mode-locked dye laser. Fig. 2A shows directly the electrical output of the Schottky photodiode, induced by the dye laser pulse. This trace was obtained with a 25 ps rise-time sampling oscilloscope (Model 7T11, 7S11, S-4 plug-ins with 7904 mainframe, Tektronix, Beaverton, OR) which was triggered by the signal from a second photodiode irradiated by the same laser. The FDHM of the pulse in Fig. 2A is approximately 90 ps and represents the true optical pulse width, smoothed by the impulse responses of the photodiode, the 5 ns of RG 58C/U coaxial cable and the sampling head itself. All these latter subsystems have rise times which are of the same order of magnitude and contribute equally to the smoothing process.

Fig. 2B shows a computer-generated autocorrelation function of the sampling oscilloscope trace of Fig. 2A. This computed autocorrelation function has a half-duration at half-maximum (HDHM) of 75 ps. In contrast, the output of the correlator for the input signal shown in Fig. 2A, shown in Fig. 2C, has a HDHM of 60 ps. The second peak that is seen at a delay of approximately 300 ps is due to an electrical reflection in the correlator network.

The results portrayed in Fig. 2 are initially quite surprising. From the foregoing analysis, one might expect the instrumental autocorrelation function to be somewhat broader than that produced upon computation, because of the finite bandwidth of the components used in the new device. However, it can be shown readily that the response of the new correlator is sufficiently rapid that the correlation function is not significantly broadened. Moreover, it is quite likely that the sampling oscilloscope trace is Fig. 2A is broader than the true pulse. Let us further examine these considerations.

The -3 db bandwidth of the photodiode signal shown in Fig. 2A is slightly less than 4 GHz, so one would not expect the autocorrelation function to be drastically smoothed by the mixer, considering its 4 GHz bandwidth. In addition, Fig. 2A might be broader than the true photodiode pulse because rise time of a sampling oscilloscope does not solely determine its time resolution; trigger jitter also contributes. The specification on the particular sampling oscilloscope used here is ± 10 ps under optimal trigger conditions. As suggested by the manufacturer, this specification is only a lower bound and the actual trigger jitter will depend on the characteristics of any particular trigger signal. Significantly, it is the autocorrelation function of the sampling oscilloscope impulse response that will act as a smoothing function on the autocorrelation of the true electrical pulse from the photodiode. Clearly, this latter fact will accentuate any distortions introduced by the sampling oscilloscope in Figs. 2A and 2B. In contrast, no such thing as jitter exists in the correlator (Fig. 2C).

Of course, the discrepency noted between Figs. 2B and 2C might also be due to mixer non-ideality. Specifically, if a threshold exists over which a signal must rise before the mixer operates properly, the correlation function would appear to be truncated somewhat. However, theory does not predict such a threshold and none has been observed experimentally.

Fig. 3 is similar to Fig. 2, but represents the output waveform and correlation functions for the argon-ion laser by itself. In this case over 90% of the duration of this electrical pulse is due to the optical pulse. Again, the function obtained with the new correlator is narrower than that obtained by computation.

V. Discussion

For the new correlator to be useful it must be able to measure features of the correlation function which indicate the real-time pulse character. The most important such feature is the relationship between the duration of the true pulse and its autocorrelation function. The HDHM of the time-dependent pulse is related to the FWHM of its autocorrelation function in a linear manner as indicated in Eq. (8),

$$FWHM_{AC} = \gamma \; FWHM_{T} \tag{8}$$

where the subscript AC and T indicate the autocorrelation and real-time parameters respectively. The factor γ is a scaling factor which is always greater than 1. The magnitude of γ is determined by the functional form of the real-time pulse shape; the more spread out the energy distribution about the center of the pulse, the larger γ becomes. For example, γ equals 1 for a rectangular pulse, whereas $\gamma = \sqrt{2}$ for a Gaussian-shaped pulse and $\gamma = 2$ for a Lorentzian pulse. These differently shaped pulses have progressively longer tails, causing the scaling factor, γ, to increase.

Table I lists the γ-factors calculated from Eq. (8) for the results shown in Fig. 2 and 3. The γ-values for the data obtained with the correlator are lower as would be expected from inspection of the correlation results. Interestingly, the γ factors in Table I are larger for the argon-ion laser pulse measurement than for the dye laser experiment, suggesting that the electrical pulse from the photodiode is more broadly distributed (rises and/or decays more slowly) when it is irradiated by the argon laser pulse. Significantly, as shown in the bottom half of Table I, the relative breadth of the correlation functions of the Ar^{+} and dye lasers are approximately the same, no matter whether computational or instrumental correlation is employed. This finding argues the validity of the new correlator output for indicating relative pulse widths, or changes in pulse shape.

The results given above clearly indicate that the new instrument can correlate very broadband (high frequency) signals. The laser sources served well to demonstrate the capabilities of the correlator but also illustrate an application of the device.

The new correlator has a host of applications, both in time-resolved laser spectroscopy and in other areas. For example, the correlator could be used as a diagnostic tool for optimization of mode-locked gas lasers. Of course, the autocorrelation function determined in this way would not uniquely determine the duration of the real-time pulse it represented, because the γ factor would not be known. However, the HDHM of the autocorrelation function is actually a better parameter to minimize than the HDHM of the pulse itself; it is not only desirable to minimize the HDHM of the time-dependent pulse, but also to have its energy distributed closely about the maximum of the pulse. A minimization of the duration of the autocorrelation function implies a minimization both of γ and of the HDHM of the real-time pulse.

The major disadvantage of this correlator is the small delay values attainable with the variable-length line stretcher (1.5 ns). This limitation implies that only broadband signals can be analyzed if an entire correlation function is to be obtained. Greater delays would be possible with alternative line stretchers but large increases in delay would limit the upper frequency cutoff of the device.

Another disadvantage of utilizing this correlation instrument for the optimization of mode-locked laser pulses is its slow scan time. The scan time of the correlator is limited by the bandwidth of the low-pass filter on the output of the mixer, from an electrical design point of view. Practically, the limit will be dictated by heat generated in the variable delay line by frictional forces involved with its movement.

Another use of the correlator in laser technology would be as a continuous monitor of the temporal characteristics of optical pulses. The output of the correlator could be used as a feedback signal to a mode-locked control system, which governs appropriate parameters such as cavity length or the frequency of an acousto-optic mode locking modulator. Such a monitoring device could be implemented by using either a four-way power splitter or two complete photodiode and correlator systems. One correlator could be set at a $\tau = 0$ situation while the second correlator could be set at a τ value, say, equal to the HDHM of the correlation function. These two DC signals could then be processed by a dividing circuit, to provide a quotient which is constant, independent of intensity, as long as the pulse shape and duration remain constant. Any changes in pulse duration or shape would then be reflected by the output of the divider and thus could be used as a feedback signal to maintain minimum pulse width.

Acknowledgments

Supported in part by the Office of Naval Research and by the Public Health Service through grants GM17904-06 and GM24473-01. Taken in part from the Ph.D. thesis of J. M. Ramsey. The authors would also like to thank L. Steinmetz who provided the Schottky photodiode used in this work.

References

1. J. S. Bendat and A. G. Piersol, Random Data: Analysis and Measurement Procedures (Wiley-Interscience, New York, 1971).
2. F. H. Lange, Correlation Techniques (Van Nostrand Rheinhold, Princeton, 1967).
3. E. R. Pike and E. Jakeman, in Advances in Quantum Electronics, edited by D. W. Goodwin (Academic Press, New York, 1974), Vol. 2, p. 1.
4. G. M. Hieftje and G. Horlick, in Contemporary Topics in Analytical and Clinical Chemistry, edited by D. M. Hercules, G. M. Hieftje, L. R. Snyder, and M. A. Evenson (Plenum Press, New York, 1978), Vol. 3, ch. 4.
5. B. J. Berne and R. Pecora, Dynamic Light Scattering (Wiley and Sons, New York, 1976).
6. B. J. Leikind and A. DeSilva, Rev. Sci. Instrum. 48, 1138 (1977).
7. A. J. DeMaria, W. H. Glenn, Jr., M. J. Brienza and M. E. Mack, Proc. IEEE, 57, 2 (1969).
8. D. J. Bradley and G. H. C. New, Proc. IEEE, 62, 313 (1974).
9. L. Steinmetz, Rev. Sci. Instrum. (in press, 1979).
10. C. K. Chan and S. O. Sari, Appl. Phys. Lett. 25, 403 (1974).

Figure Captions

Fig. 1. Schematic diagram of the new correlation instrument configured for autocorrelation measurements.

Fig. 2 Evaluation of the new correlator's performance in the measurement of pulses from a synchronously pumped mode-locked dye laser. A. Output of irradiated Schottky photodiode, measured with 25 ps rise-time sampling oscilloscope. B. Computer-generated autocorrelation function of A. C. Autocorrelation function of Schottky photodiode output determined with the new correlation instrument. See text for discussion.

Fig. 3 Evaluation of the new correlator for the examination of a mode-locked argon-ion laser. A. Output of irradiated Schottky photodiode measured with 25 ps rise-time sampling oscilloscope. B. Computer-generated autocorrelation function of A. C. Autocorrelation function of Schottky photodiode output determined with the new correlation instrument.

Table I.

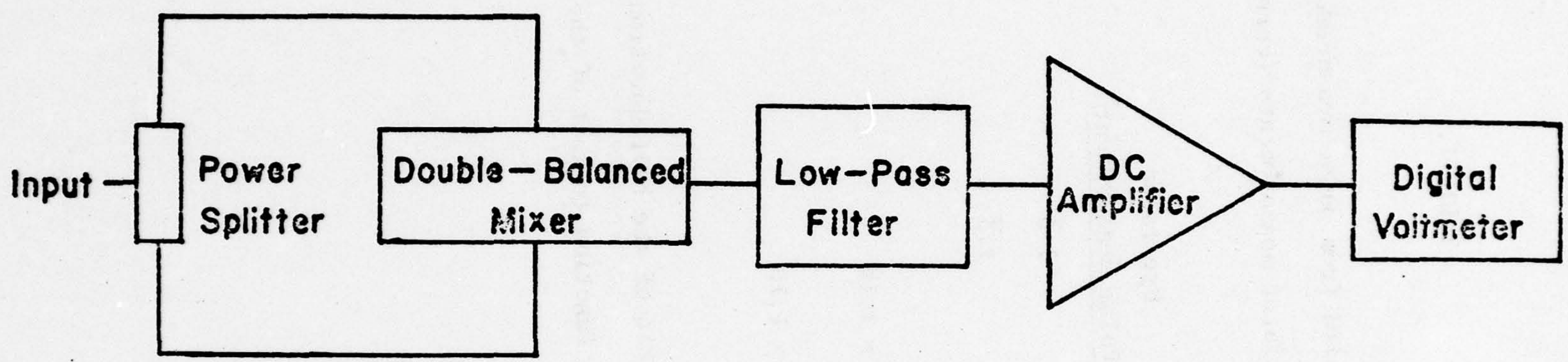
γ-factors calculated from pulse measurements (calc.) and correlator measurements (corr).[a]

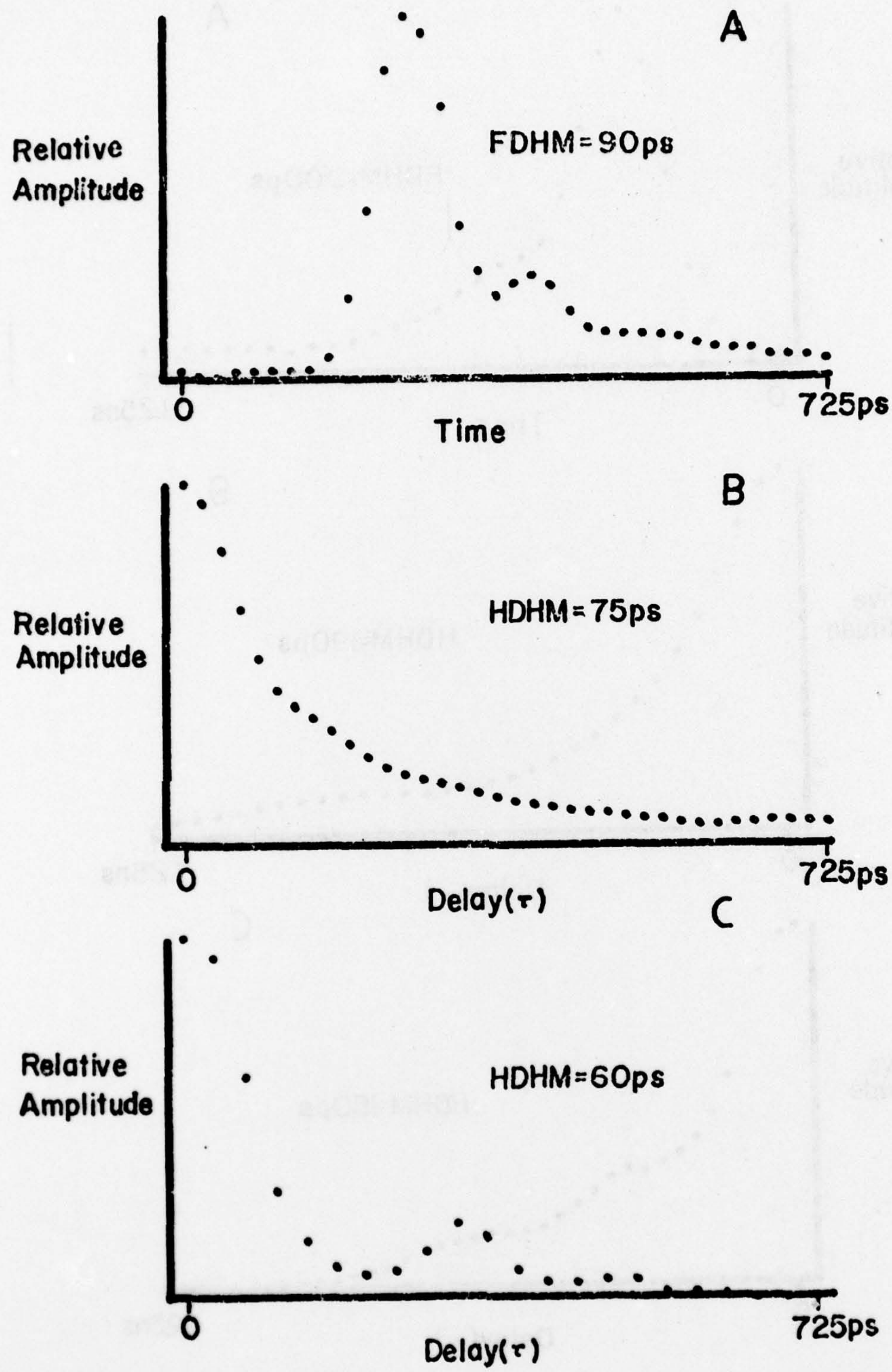
	Dye laser Pulse Measurement	Ar^+ laser Pulse Measurement
γ_{calc}	$1.\overline{6}$	1.90
γ_{corr}	$1.\overline{3}$	1.50

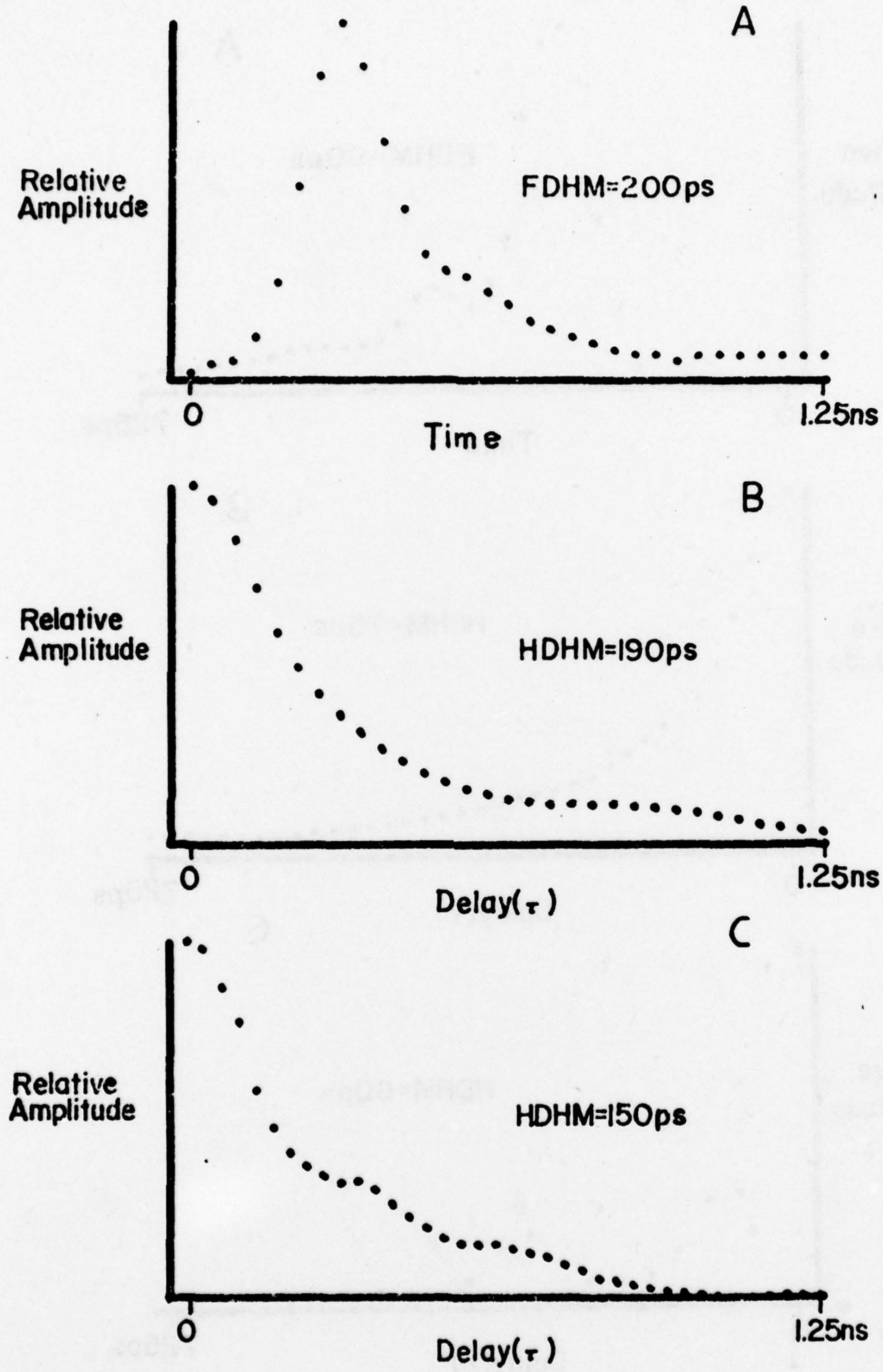
$$(\gamma^{Ar^+}/\gamma^{Dye})_{calc} = 1.19$$

$$(\gamma^{Ar^+}/\gamma^{Dye})_{corr} = 1.15$$

a. γ is defined as the ratio of the half-duration at half-maximum (HDHM) of the autocorrelation function to that of the original real-time waveform.


Input
Power
Splitter
Double—Balanced
Mixer
Low—Pass
Filter
DC
Amplifier
Digital
Voltmeter


A
Relative Amplitude
FDHM=90ps
0
725ps
Time
B
Relative Amplitude
HDHM=75ps
0
725ps
Delay(τ)
C
Relative Amplitude
HDHM=60ps
0
725ps
Delay(τ)


A
Relative Amplitude
FDHM=200ps
0
1.25ns
Time
B
Relative Amplitude
HDHM=190ps
0
1.25ns
Delay(τ)
C
Relative Amplitude
HDHM=150ps
0
1.25ns
Delay(τ)

TECHNICAL REPORT DISTRIBUTION LIST, GEN

	No. Copies
Office of Naval Research 800 North Quincy Street Arlington, Virginia 22217 Attn: Code 472	2
ONR Branch Office 536 S. Clark Street Chicago, Illinois 60605 Attn: Dr. George Sandoz	1
ONR Branch Office 715 Broadway New York, New York 10003 Attn: Scientific Dept.	1
ONR Branch Office 1030 East Green Street Pasadena, California 91106 Attn: Dr. R. J. Marcus	1
ONR Area Office One Hallidie Plaza, Suite 601 San Francisco, California 94102 Attn: Dr. P. A. Miller	1
ONR Branch Office Building 114, Section D 666 Summer Street Boston, Massachusetts 02210 Attn: Dr. L. H. Peebles	1
Director, Naval Research Laboratory Washington, D.C. 20390 Attn: Code 6100	1
The Assistant Secretary of the Navy (R,E&S) Department of the Navy Room 4E736, Pentagon Washington, D.C. 20350	1
Commander, Naval Air Systems Command Department of the Navy Washington, D.C. 20360 Attn: Code 310C (H. Rosenwasser)	1

	No. Copies
Defense Documentation Center Building 5, Cameron Station Alexandria, Virginia 22314	12
U.S. Army Research Office P.O. Box 1211 Research Triangle Park, N.C. 27709 Attn: CRD-AA-IP	1
Naval Ocean Systems Center San Diego, California 92152 Attn: Mr. Joe McCartney	1
Naval Weapons Center China Lake, California 93555 Attn: Dr. A. B. Amster Chemistry Division	1
Naval Civil Engineering Laboratory Port Hueneme, California 93401 Attn: Dr. R. W. Drisko	1
Professor K. E. Woehler Department of Physics & Chemistry Naval Postgraduate School Monterey, California 93940	1
Dr. A. L. Slafkosky Scientific Advisor Commandant of the Marine Corps (Code RD-1) Washington, D.C. 20380	1
Office of Naval Research 800 N. Quincy Street Arlington, Virginia 22217 Attn: Dr. Richard S. Miller	1
Naval Ship Research and Development Center Annapolis, Maryland 21401 Attn: Dr. G. Bosmajian Applied Chemistry Division	1
Naval Ocean Systems Center San Diego, California 91232 Attn: Dr. S. Yamamoto, Marine Sciences Division	1

Encl 1

TECHNICAL REPORT DISTRIBUTION LIST, 051C

	No. Copies
Dr. M. B. Denton University of Arizona Department of Chemistry Tucson, Arizona 85721	1
Dr. R. A. Osteryoung Colorado State University Department of Chemistry Fort Collins, Colorado 80521	1
Dr. B. R. Kowalski University of Washington Department of Chemistry Seattle, Washington 98105	1
Dr. S. P. Perone Purdue University Department of Chemistry Lafayette, Indiana 47907	1
Dr. D. L. Venezky Naval Research Laboratory Code 6130 Washington, D.C. 20375	1
Dr. H. Freiser University of Arizona Department of Chemistry Tuscon, Arizona 85721	
Dr. Fred Saalfeld Naval Research Laboratory Code 6110 Washington, D.C. 20375	1
Dr. H. Chernoff Massachusetts Institute of Technology Department of Mathematics Cambridge, Massachusetts 02139	1
Dr. K. Wilson University of California, San Diego Department of Chemistry La Jolla, California 92037	1
Dr. A. Zirino Naval Undersea Center San Diego, California 92132	1
Dr. John Duffin United States Naval Postgraduate School Monterey, California 93940	1
Dr. G. M. Hieftje Department of Chemistry Indiana University Bloomington, Indiana 47401	1
Dr. Victor L. Rehn Naval Weapons Center Code 3813 China Lake, California 93555	1
Dr. Christie G. Enke Michigan State University Department of Chemistry East Lansing, Michigan 48824	1
Dr. Kent Eisentraut, MBT Air Force Materials Laboratory Wright-Patterson AFB, Ohio 45433	1
Walter G. Cox, Code 3632 Naval Underwater Systems Center Building 148 Newport, Rhode Island 02840	1